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TR 67-40

TECHNICAL REPORT NO. 67-40

MULTICOMPONENT STRAIN SEISMOGRAPH

Quarterly Report No. 8, Project VT/5081

1 April to 30 June 1967

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GEOTECH

A TELEDYNE COMPANY

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Sponsored by

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ARPA Order No. 624

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GEOTECH
A TELEDYNE COMPANY
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Garland, Texas

18 July 1967

IDENTIFICATION

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Contractor:	The Geotechnical Corporation Garland, Texas
Date of Contract:	1 July 1965
Amount of Contract:	$393,361
Contract No.	AF 33(657)-15288
Contract Expiration Date	31 December 1967
Project Manager	R. C. Shopland, BR 1-2561

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ILLUSTRATIONS

ILLUSTRATIONS, Continued

ABSTRACT

Use of an electromagnetic calibrator in place of the magnetostrictive calibrator on the vertical strain seismometer has eliminated phase discrepancies. Results show that all strain and inertial systems are matched within 4 degrees between 0.1 and 3 cps and within 10 degrees out to 10 cps. An analysis of coherency, phase, and spectra of seismic noise and signals computed by a fast transform BLACKY program shows that the instruments are operating according to theory. Comments relating to the character of the seismic noise are also given. The effects of temperature changes and wind on operation of the horizontal strain seismometers are discussed. Operation of a matched long-period horizontal strain-inertial combination for directional discrimination of long-period surface waves is also discussed.

MULTICOMPONENT STRAIN SEISMOGRAPH

1. INTRODUCTION

This report discusses technical findings and accomplishments in a program of strain seismology performed under Contract AF 33(657)-15288, S/A No. 2, in the period 1 April to 30 June 1967. The work reported herein primarily covers development of a system of 3-component strain and 3-component short-period inertial seismographs having matched amplitude and phase responses in the frequency range 0.01 - 10 cps.

This report is submitted in compliance with Item A002 of Contract Data Requirements List, Contract AF 33(657)-15288, S/A No. 2. The report is presented in the same sequence as the tasks in the Statement of Work. The Statement of Work is included as an appendix.

During the reporting period the following objectives received the main emphasis:

a. Restoration of the strain system at WMSO to an operating condition following severe damage sustained during a lightning storm on 10 April 1967.

b. Recording 3-component strain data with the new "three-cycle" system for the measurement of coherency, phase, and spectra.

c. Resolving apparent discrepancies in phase response of the vertical strain seismograph and magnetostrictive (MS) calibrator;

d. Comparison of the steel-cased and plastic-cased boreholes;

e. Evaluation of environmental effects on the operation of horizontal strain seismometers;

f. Evaluation of the potential of a long-period strain directional array.

Major accomplishments were as follows:

a. Milestone No. 15, requiring in situ monitoring of the motion of the MS calibrator in the vertical strain seismometer, was determined to be unnecessary.

b. The electromagnetic (EM) calibrator was determined to be an effective replacement for the MS calibrator on the vertical strain seismometer.

c. The phase relationship between fixed and free ends of the horizontal strain seismometer has been measured (Milestone No. 16).

d. Modifications have been completed and matched frequency responses obtained for the long-period north strain seismograph and the long-period inertial seismograph (Milestone No. 17).

e. An analysis of the effect of wind and temperature changes on operation of the horizontal strain seismometers has been completed using short-term data (Milestone No. 18).

f. Coherency, phase and spectra among vertical strain, horizontal strain, and inertial systems have been computed by a fast transform BLACKY program (FTBLKY 2). Conclusions regarding proper response of the instruments are stated in this report. Some comments relating to the character of the seismic noise are also given.

g. The vertical strain seismometers in the plastic-cased and steel-cased boreholes at WMSO were interchanged. Comparison of data before and after the interchange is incomplete.

2. INSTRUMENTATION DEVELOPMENT

2.1 ELECTROMAGNETIC CALIBRATOR FOR VERTICAL STRAIN SEISMOMETER

Tests of the MS calibrator discussed in Technical Report 66-93 showed that phase discrepancies noted in the output of the vertical strain seismometer were most likely in the calibrator. To fully determine whether the problem was in the calibrator or in the seismometer two methods were available: (1) Mount a displacement transducer near the calibrator to directly measure the phase and amplitude response of the MS calibrator, or (2) replace the unit with an EM calibrator using the same principle as those on the horizontal seismometers. It was anticipated that the first method (monitoring of the MS calibrator motion in situ) would serve only to verify suspicions regarding the MS calibrator response. Therefore, it was decided to directly circumvent problems in the MS calibrator by replacing it with an EM unit -- an approach which proved later to be more direct and far less costly.

2.1.1 Field Tests

During early May, an experimental model of the EM calibrator was installed on one of the vertical strain seismometers at WMSO. Testing was completed on 24 May with excellent results. Figure 1 shows the improvement in the phase response of the vertical strain seismometer under operational conditions.

2.1.2 Conclusions

The EM has been shown to be far superior to the MS calibrator as a means of determining the actual response of the vertical strain seismometer. In addition to the obvious advantage of a 10 to 15-degree improvement in the phase response, the EM calibrator output is linear with respect to driving current and frequency whereas the MS calibrator is not. Furthermore, the EM calibrator does not require bias current. For these reasons, it is recommended as a replacement for the MS calibrator on the vertical strain seismometers.

2.2 PHASE RESPONSE OF STRAIN SEISMOMETERS

The variable-capacitance (VC) transducer was used to determine the phase responses of the vertical and horizontal seismometers after installation of the EM calibrator on the vertical instrument. The responses were measured on the free ends of the northeast strain seismometer (SNE) and the vertical strain seismometer in the plastic-cased borehole (SZ_{2B}). Both curves show zero degree lag from 0.3 to 1.5 cps, increasing to approximately 17 degrees lag at 10 cps.

A comparison of figure 1 (curve A) and figure 2 (curve A) shows the similarity in phase response between the two seismometers.

In order to determine whether the EM calibrator caused part of this phase shift, the VC transducer was mounted near the calibrators on the east and northeast strain instruments. Phase responses in both cases indicated zero degrees lag from 0.3 to 2.0 cps, increasing to approximately 6 degrees lag at 10 cps. Figure 2 (curve B) shows the response of SNE near the calibrator. This phase error is not believed to be in the calibrator itself since seismometer reasonances noted on the free end of the quartz standard are measureable near the fixed end and can cause phase errors.

The phase response of the VC transducer was measured in the laboratory using the shake table and found to be essentially flat in the frequency band of interest.

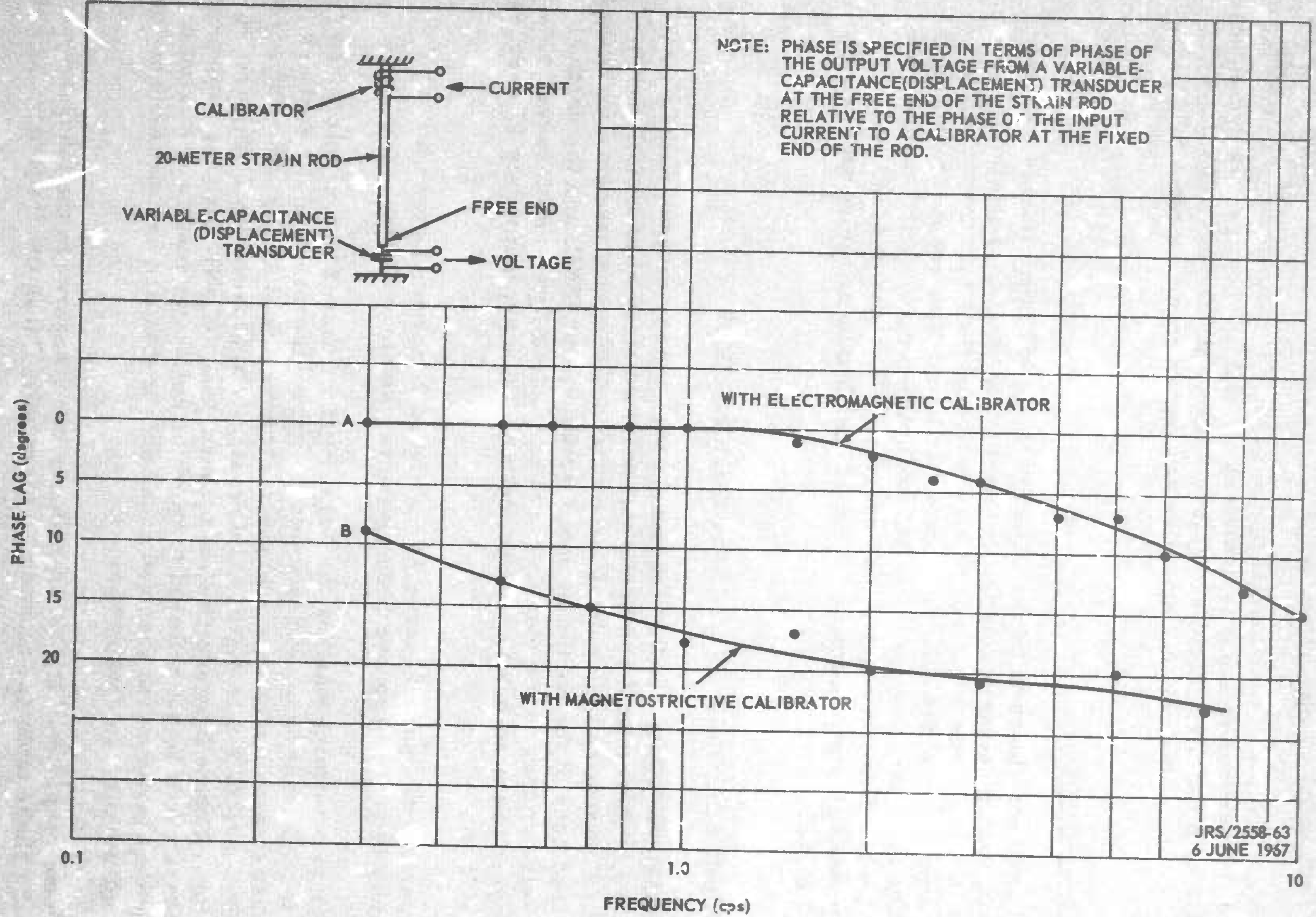

Figure 1. Phase response of the vertical strain seismometer using the variable capacitance transducer

G 2902

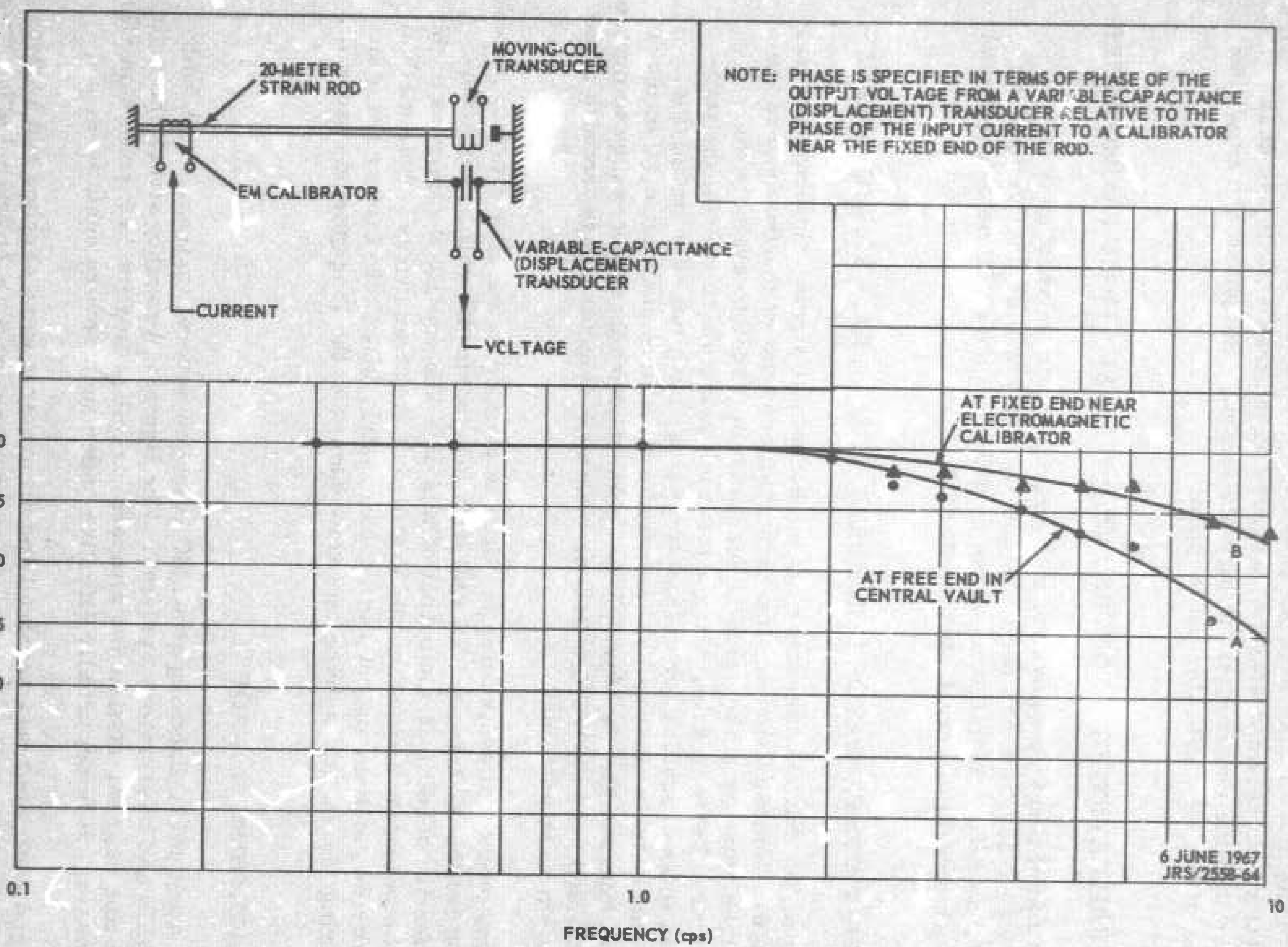

Figure 2. Phase response of the northeast horizontal strain seismometer using the variable capacitance transducer

G 2903

In view of the close match between phase responses of the vertical and horizontal strain seismometer as measured at the free end, it has been requested that the requirement to directly measure the phase and amplitude response of the MS calibrator be dropped.

2.3 MODIFICATION OF ANCHORS FOR VERTICAL STRAIN SEISMOMETER

Fabrication of larger anchors for the vertical strain seismometer in the plastic-cased borehole has been completed. They will replace temporary shimmed anchors. Installation of the modified anchors will be delayed until it is convenient to interrupt operation.

2.4 DRIFT COMPENSATOR FOR HORIZONTAL STRAIN SEISMOMETERS

Testing of the drift compensator for the horizontal strain seismometers has continued. Compensation of long-term displacement of the free end of the strain tube relative to the earth is necessary in order to evaluate the VC transducer. Tests to date, using a feedback principle to control the temperature to an expanding (or contracting) slug, have not been promising. The secular strain monitor has indicated a maximum constant drift of more than two microns per day during one week. The feedback necessary to control this drift and keep the VC transducer within its dynamic range tends to cause the system to be unstable.

A second method of controlling the drift is planned in the near future. Instead of using feedback, a second VC unit with low sensitivity will be installed. The effective secular strain output of this unit will control the current to the drift compensator mounted on the high sensitivity transducer. This method will provide positive control and, if successful, will avoid further delay in comparing the VC and moving coil transducers in the long-period spectrum.

2.5 LIGHTNING DAMAGE

On 10 April 1967, lightning at WMSO damaged several instruments in both the strain and observatory systems. The lightning probably struck the main power line near the station and although circuit protection is installed on all instruments, it is not usually effective under such severe conditions.

Damaged equipment was repaired and all systems were checked and adjusted where necessary. The system was again operational on 21 April 1967. This damage necessitated approximately 30 man-days of effort for repairs and delayed progress on several tests planned during the quarter.

3. SEISMOGRAPH DEVELOPMENT

3.1 PHASE RESPONSES OF THE STRAIN AND INERTIAL SEISMOGRAPHS

After installation of the EM calibrator on the vertical strain seismometer, phase responses were conducted to determine whether all seismographs were matched. Figure 3 shows close matching between the vertical inertial (SPZ) and the vertical strain (SZ) seismographs in the frequency range 0.2 to 10 cps. The maximum mismatch is 6 degrees; average mismatch is 3 degrees. Figure 4 shows a similar match between the north east inertial (SPNE) and the northeast strain (SNE). The maximum mismatch in this case is 5 degrees and the average mismatch 3 degrees. A comparison of figures 3 and 4 shows that the maximum mismatch between the four systems is 7 degrees.

The phase response match between these four systems is typical among all seismographs and is considered sufficient for final evaluation. With the exception of routine maintenance, further efforts to improve the phase responses are not planned.

3.2 LONG-PERIOD HORIZONTAL STRAIN

During the early part of the quarter intermittent instrument noise in the long-period north strain seismograph (SNL) became serious. This noise was found to be caused by stray leakage to ground in the seismometer data coil. A new coil was manufactured and installed on 7 June. After a normal settling period, routine operation was resumed.

Modification and testing of SNL was completed on schedule. An amplitude response indicated that SNL is matched within 10 percent to the WMSO long-period inertial seismograph (NLL). This match is considered sufficient for the purpose of evaluating the directional array capabilities of long-period strain.

SNL and NLL data are now being routinely recorded on tape and film. Several earthquakes have been recorded which indicate favorable operation. Off-line data processing will be started in the near future.

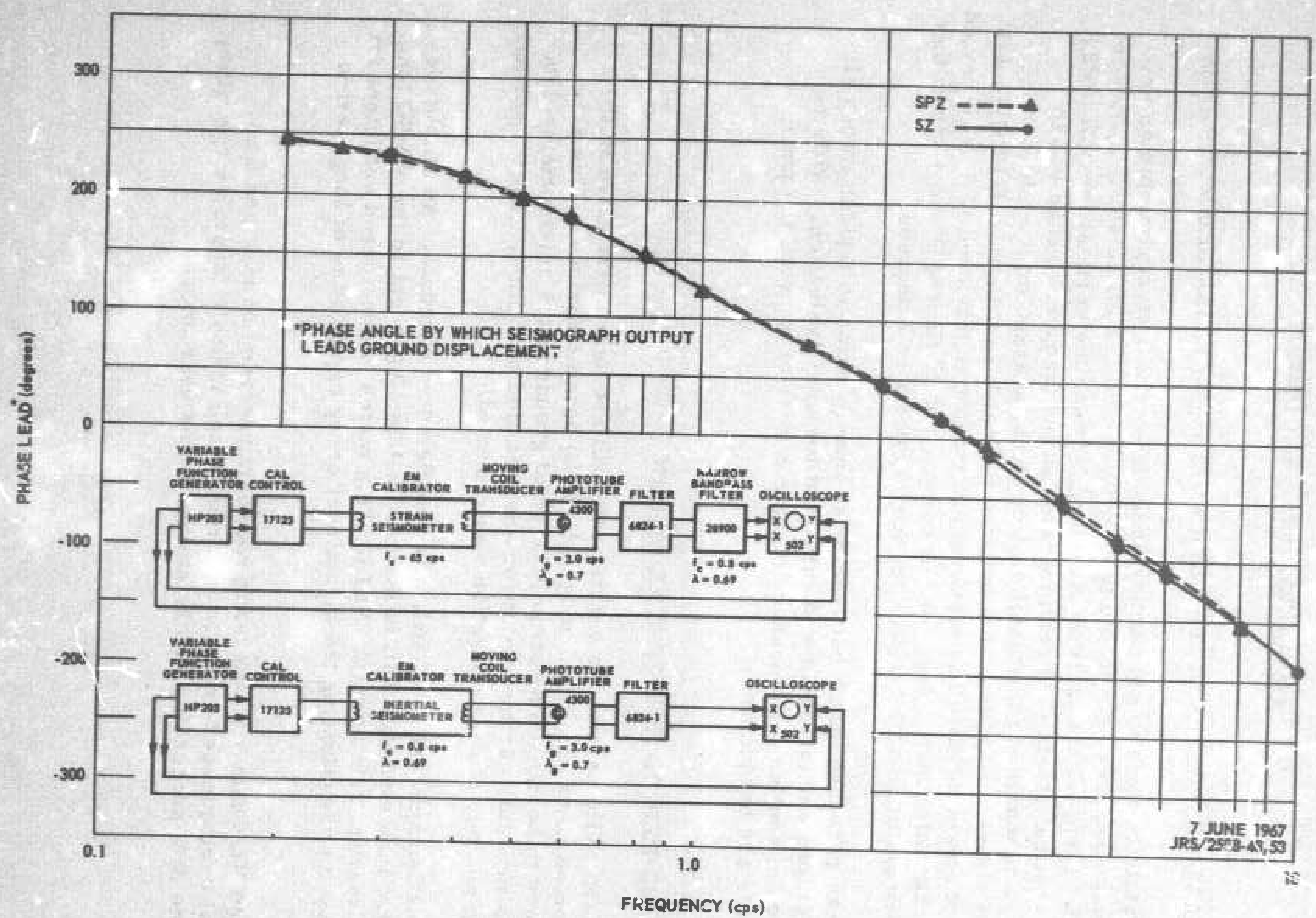

Figure 3. Phase response to ground displacement of short-period vertical inertial (SPZ) and short-period vertical strain (SZ) seismographs showing close matching

G 2904

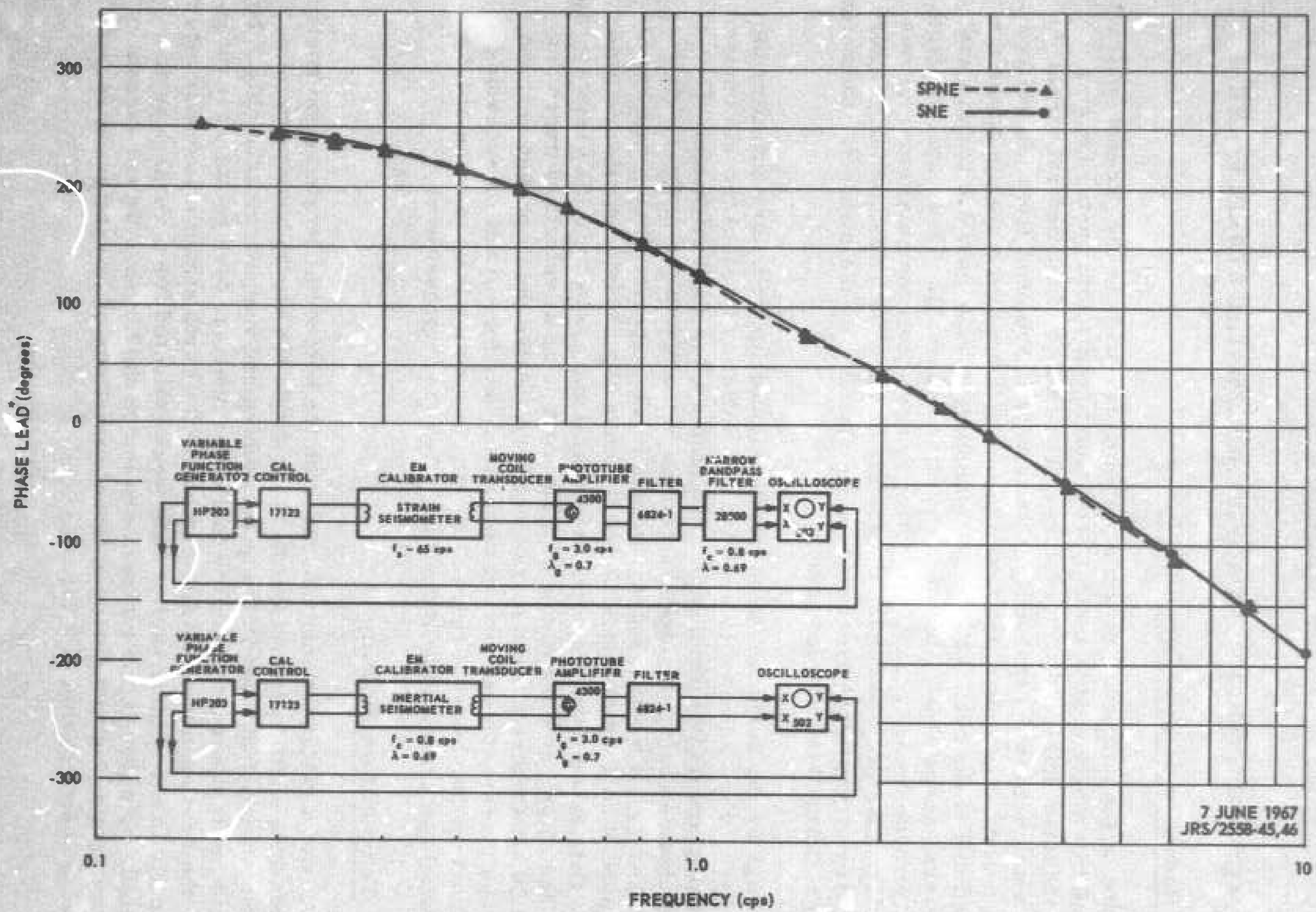

Figure 4. Phase response to ground displacement of short-period northeast inertial (SPNE) and short-period northeast strain (SNE) seismographs showing close matching

G 2905

4. EVALUATION

4.1 EVALUATION OF THE IMPROVED HORIZONTAL STRAIN HOUSING

4.1.1 Reduction of Wind-Generated Noise

Operation of the horizontal strain seismometers prior to the present contract revealed two major environmental problems in the seismometer housing, wind-generated noise and temperature. The ceiling of the central strain vault, which houses the transducers, was only 1.2 meters from the surface of the ground. The tops of the tank vaults which house the anchor plates for the fixed end of the north and west seismometers were only 2.6 meters and 1.8 meters, respectively, below the surface (figure 5). These shallow depths did not provide the necessary protection against environmental noise as was originally expected. To reduce the effects of the wind noise and temperature, 1.3 meters of additional overburden were placed over the strain seismometer housings during this contract period.

Recordings by the north and west strain seismographs, before and after the above work, were selected to evaluate the reduction in recorded wind noise. Both analog and digital techniques were employed in the evaluation. The results obtained using the digital technique were discussed in Quarterly Report No. 7, TR 67-15. Measurements of short-period analog data from the improved horizontal strain housing show a significant reduction in wind noise. Data taken from the north strain (SN) and east strain (SE) seismographs before the improvement had discernable wind noise at velocities exceeding 10 and 20 kilometers per hour, respectively. After the improvement, the noise was discernable on both seismographs only for velocities exceeding 35 kilometers per hour. Figure 5 is a graph showing the response of SN and SE to wind-generated noise before and after the improvements.

4.1.2 Temperature Stability

Operation of a displacement transducer on the horizontal strain seismometer requires long-term temperature stability within the strain housing to minimize dimensional changes in the quartz tubing and transducer assembly. To evaluate the temperature stability inside the housing, four points were monitored, the north and west strain members, the north strain transducer mount and the air in the central vault. Data were collected for several days and evaluated. Changes in the temperature inside the housing did not exceed ±0.2 centigrade degrees during external variations of 25 centigrade degrees occurring over a period of 6 days.

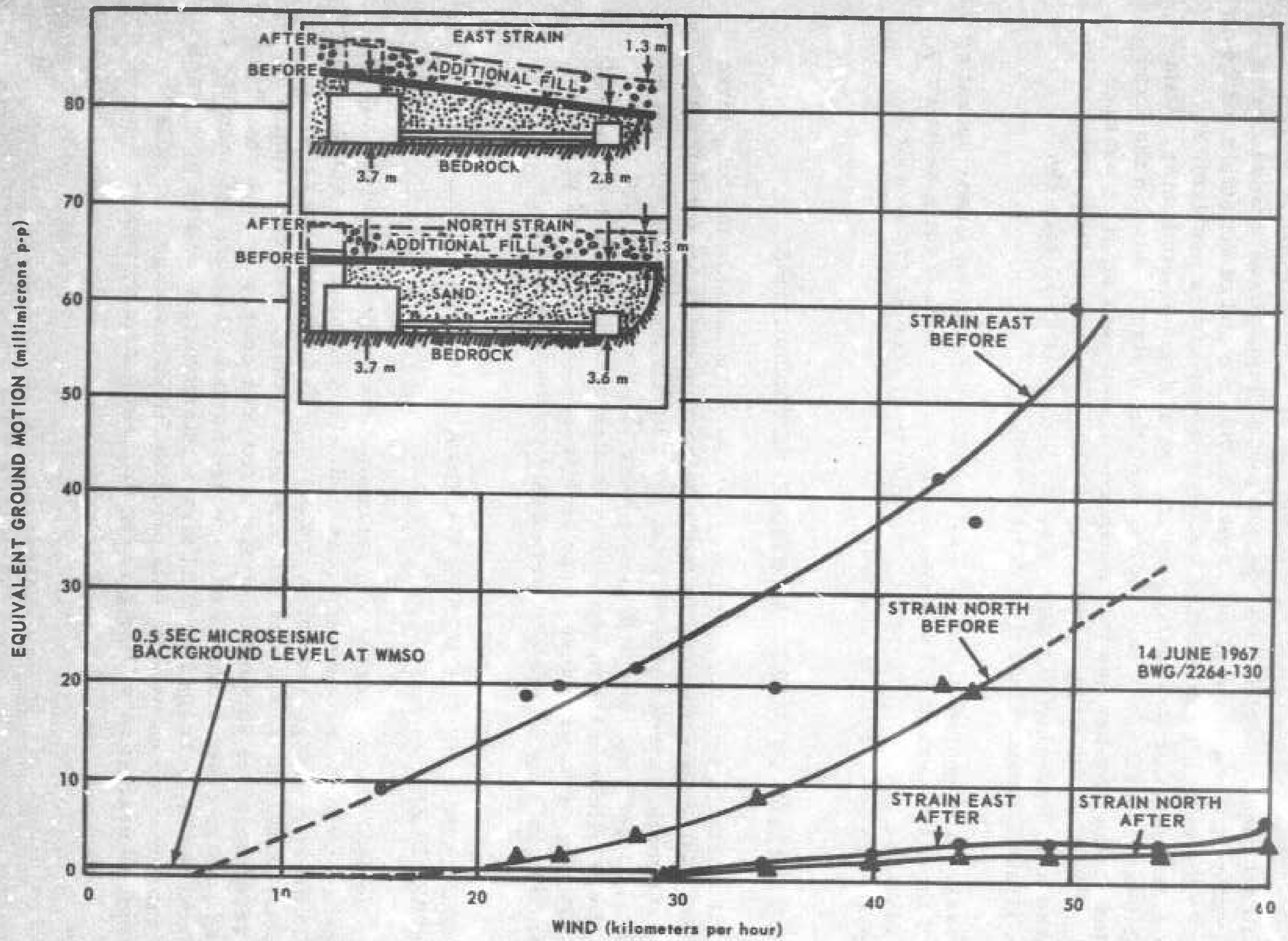

Figure 5. Graph showing response of the north and east strain seismometers to wind noise before and after the addition of 1.3 meters of overburden on the strain seismometer housings. Data were taken from short-period seismographs.

G 2906

4.1.3 Secular Strain

An additional requirement for the operation of a displacement transducer is compensation for long-term displacement of the free end of the strain member relative to the earth. To determine the seriousness of this problem, a secular strain monitor was installed on the west strain seismometer. Data taken between 3 April and 5 May 1967 showed the distance between the fixed end of the strain member and the transducer was increasing at an average rate of 2.1 microns per day. From 5 to 12 May 1967 the average rate decreased to 1.0 microns per day. For the 4 days after 12 May 1967, secular strain fluctuated less than 0.5 microns.

The average daily secular strain of 2.1 microns exceeds the linear operating range of the displacement transducer which is ±1.0 micron for a sensitivity of 3.0 volts per micron. To reduce the effects of secular strain a drift compensator is being built and tested.

4.2 RELIABILITY OF VERTICAL STRAIN SEISMOMETERS

The vertical strain seismometers have proved to be reliable for long-term operation. After operating continuously without maintenance for 6 months both seismometers were removed from their boreholes and all sections were opened for inspection. Minor oil leaks were found around the emergency removal weak-links in the upper anchor section of both seismometers. All other "O" ring seals were found to be leak free. After removal of oil and reassembly, both seismometers were again put into operation.

4.3 COMPARISON OF THE STEEL-CASED AND PLASTIC-CASED BOREHOLES

On 16 May 1967 the vertical strain seismometers in the steel-cased and plastic-cased boreholes were interchanged. Data from the two seismometers prior to the interchange have been compared with data from the crossed horizontal strain seismometers and with one another. The data from the steel-cased borehole seismometer displayed poor coherency with data from both the plastic-cased borehole and crossed horizontal strain seismometers. Data from the interchanged vertical strain seismometers will be processed in the same manner as was the data prior to the interchange. Results from the complete evaluation will be given in the next quarterly report.

5. APPLICATIONS

5.1 SPECTRA, PHASE AND COHERENCE

Coherence and phase between strain seismograms and coherence between vertical strain and inertial seismograph recordings has been computed. Spectra of each seismogram used to compute coherence have also been obtained to assist in interpretation. These data are discussed, where relevant, in the following sections of this report.

All data analyzed were digitized at a rate of 20 samples per second. A Hanning window, 10 percent lags, and sample length of 3700 samples were used on each time series processed.

5.2 VERIFICATION OF THE PROPER OPERATION OF THE STRAIN SEISMOGRAPHS

5.2.1 General

Prior to the addition of a second 3-component strain system at WMSO it was impossible to conclusively attribute the observed differences between the vertical and summed horizontal strain seismograms to either seismograph malfunctions or theoretical limitations resulting from simplified assumptions. During 1966 the second 3-component system became operational providing, for the first time, a control by which the strain seismographs could be accurately evaluated.

In the past, the relationships anticipated between strain and inertial seismograms, and vertical and horizontal strain seismograms had been the only tools available for assessing the degree to which the WMSO strain seismograms were recording in accordance with theory. The relationship between strain and inertial seismograms provided only limited information due to inherent differences in the seismograph responses to seismic waves. The relationship between the vertical and summed horizontal strain seismograms, although expected to be approximately proportional, was insufficient for accurate evaluation due to a problem at low frequencies with the original vertical strain seismograph. Since the addition of a second vertical strain the problem has become apparent and is illustrated in figure 6. This shows the coherence squared between the two vertical strains, and between each vertical strain and the summation of the NE and NW horizontal strains. Reference to the vertical strain in the following, therefore is restricted to the new seismograph located in the plastic-cased borehole. No attempt to evaluate the original vertical strain seismograph, located in the steel-cased borehole, has been made at this time.

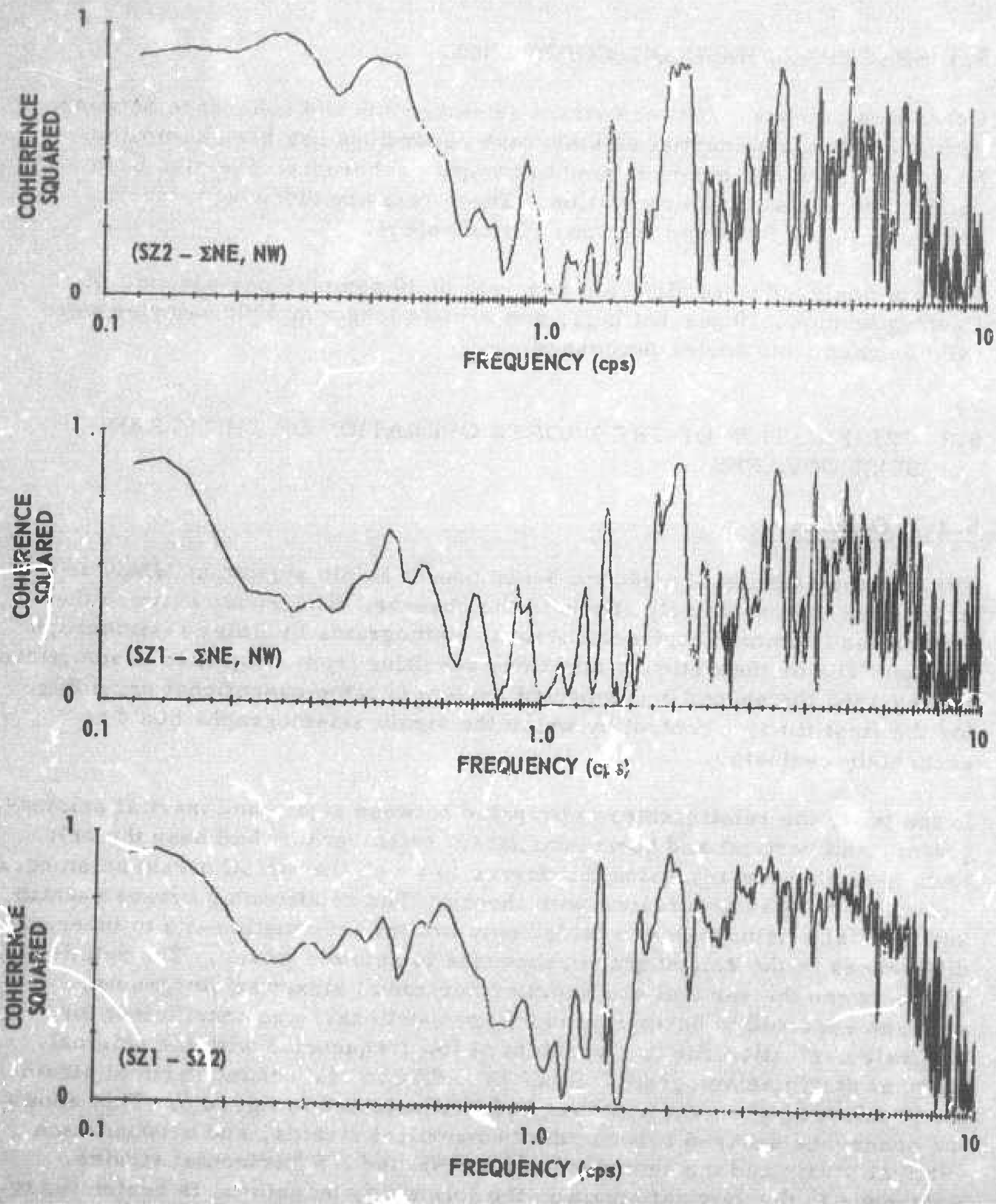

Figure 6. Coherence between the vertical strain located in the new borehole (SZ2) and the crossed strains (ΣNE, NW) top, coherence between the vertical strain located in the original borehole (SZ1) and the crossed strains (ΣNE, NW) center, and coherence between the two vertical strains (SZ1 – SZ2) bottom

G 2907

5.2.2 Horizontal Strain Seismographs

The addition of two orthogonal horizontal strain seismographs to the existing 3-component system at WMSO has provided a particularily effective method of evaluating the strain seismographs. The method is simply a comparison of the summed outputs, hence crossed strains, of each pair of orthogonal horizontal strain seismographs. The new strain seismographs are oriented $+45^{\circ}$ and -45° from the north strain, that is, the crossed strain systems are oriented 45° from one another rather than in the same direction. The effectiveness of the method of evaluation lies in the theoretical equality of any two crossed strains, independent of directional orientation or wave type. Thus, the degree of similarity between the two crossed strains is used to establish that the WMSO horizontal strain seismographs are operating in accordance with theory.

Coherence between the crossed strains, presented as coherence squared, along with the phase of the cross spectra and spectra of the individual crossed strains is illustrated in figure 7. The coherence is very high except near 1 cps, and above 7 cps. Above 7 cps the seismic noise is very low and approaches tape noise, a condition that could be expected to result in low coherence. The saddle centered near 1 cps in figure 7 appears to correlate with the spectral lows of the individual crossed strain recordings.

Coherence between the crossed strains was also computed for a sample containing substantial 1 cps signal, the initial arrival of a regional event, figure 8. This sample shows high coherence near 1 cps which lends support to correlation of relatively low coherence with spectral lows.

Two additional samples of microseisms, taken over a period of 2 months, have been used to compute coherence between the crossed strains. The results are similar to those presented in figure 7 and therefore are not illustrated. However, they do show that very high coherence was not peculiar to a specific sample and indicate, along with the sample containing earthquake signal, that the crossed strains are highly coherent independent of time and wave type.

Since coherence is a measure of the linear dependence of one time series on another and does not necessarily imply equality, the degree to which the two sets of crossed strains approach an equality is shown in figure 9.

In conclusion, the similarity of the crossed strains is sufficient to establish, within the limits of acceptable tolerance, that the WMSO horizontal strain seismographs are operating in accordance with theory.

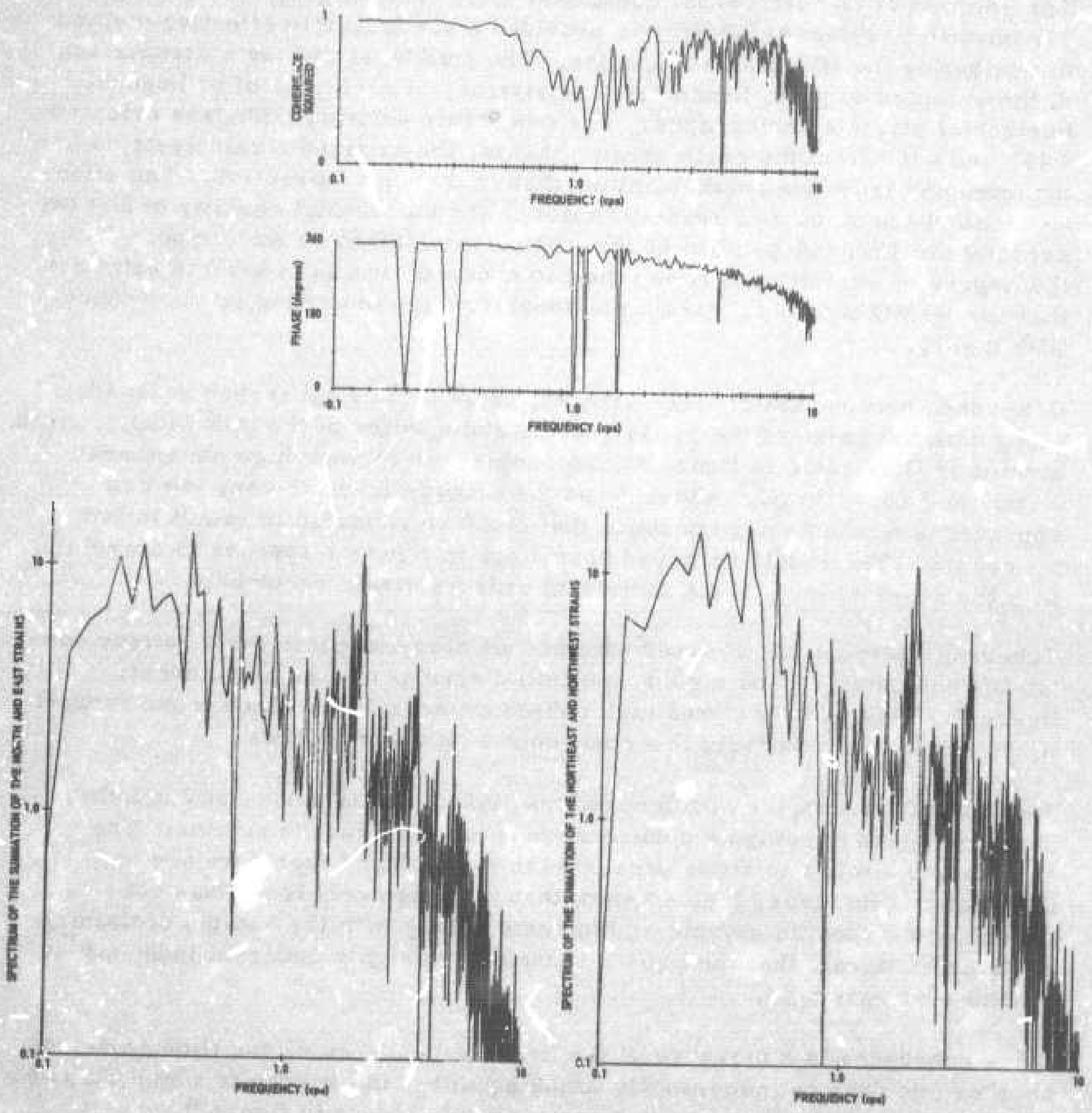

Figure 7. Coherence and phase between and spectra of the summations of the north and east strain and northeast and northwest strain seismograph recordings of microseisms

G 2908

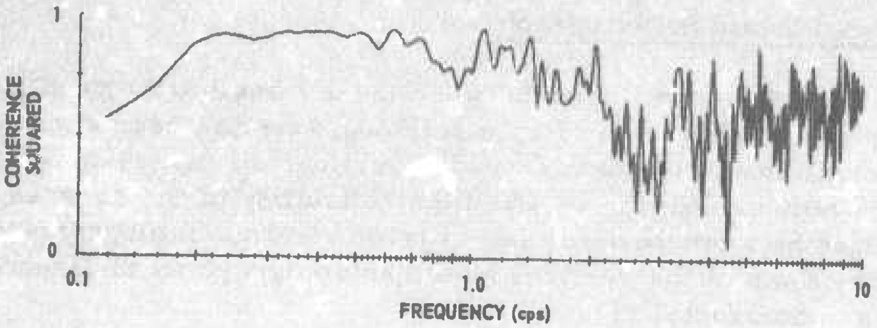

Figure 8. Coherence between the summations of the north and east strain and northeast and northwest strain seismograph recordings of the initial arrival of a regional event G 2909

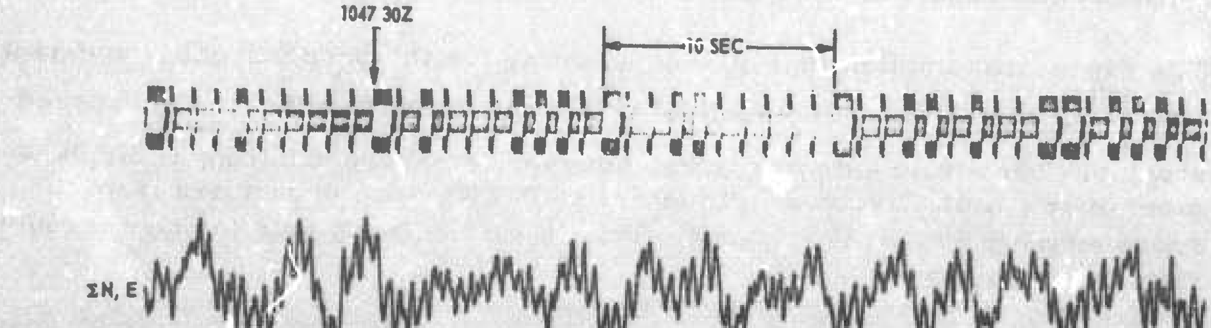

Figure 9. Seismogram of microseisms illustrating the similarity between the two sets of crossed strains (ΣN, E and ΣNE, NW). Bottom trace is ΣN, E minus ΣNE, NW

G 2910

5.2.3 Vertical Strain Seismograph

An examination of the similarity between the summed orthogonal horizontal (crossed strains) and vertical strain seismograms has been employed to evaluate the validity of the data from the vertical strain seismograph located in the new borehole. Having verified the reliability of the crossed strains, dissimilarities between vertical and crossed strain seismograms result from either malfunctions of the vertical strain seismograph or differences inherent in vertical and horizontal strain.

Romney (1964) pointed out that $\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} = \frac{2\mu + \lambda}{\lambda} \frac{\delta w}{\delta z}$ is a relationship among strain where the normal stress is zero. In the above expression, u, v, and w are the displacements in the x, y, and z direction (z normal to the surface) and λ and μ are the Lame' constants.

The expression implies that by compensating for the proportionality constant, $-\frac{2\mu + \lambda}{\lambda}$, the output of the vertical strain can be made equal to the crossed strains. The strain seismographs, however, measure differential displacement over a finite distance, 18 meters at WMSO, thus departures from the above equality can be anticipated. This is particularily true for high frequency signals of short wave length.

At a given frequency the difference between vertical and horizontal differential displacement is found theoretically to be dependent upon wave type, that is, transverse (SV), longitudinal, or Rayleigh. One will note that the relationship of the components of strain in the above expression shows no such dependence. Nevertheless, microseisms at a given frequency composed of a mixture of wave types will not be recorded equally by the vertical and crossed strains. Furthermore, the vertical and crossed strains will be incoherent if there is no predominant wave type.

Coherence between the vertical and crossed strains computed for a sample of microseisms is presented in figure 10 as coherence squared. Two additional samples (not shown) gave results similar to those of figure 10.

From figure 10 the coherence at low frequencies is very high. Centered near 1 cps is a saddle which again probably correlates with the trough observed in the spectra. At 2 and 3 cps, spectral highs, the coherence is high. This indicates the signal at these frequencies consists primarily of just one or two wave types that are not necessarily the same at both frequencies. However, signals at frequencies above 0.7 cps generally are not highly coherent, which could be explained by a mixture of wave types.

Figure 6 shows the coherence between the two vertical strains to be very high at frequencies above 1.5 cps as is the coherence between the crossed strains. That is, high coherence is observed between seismograms of similar

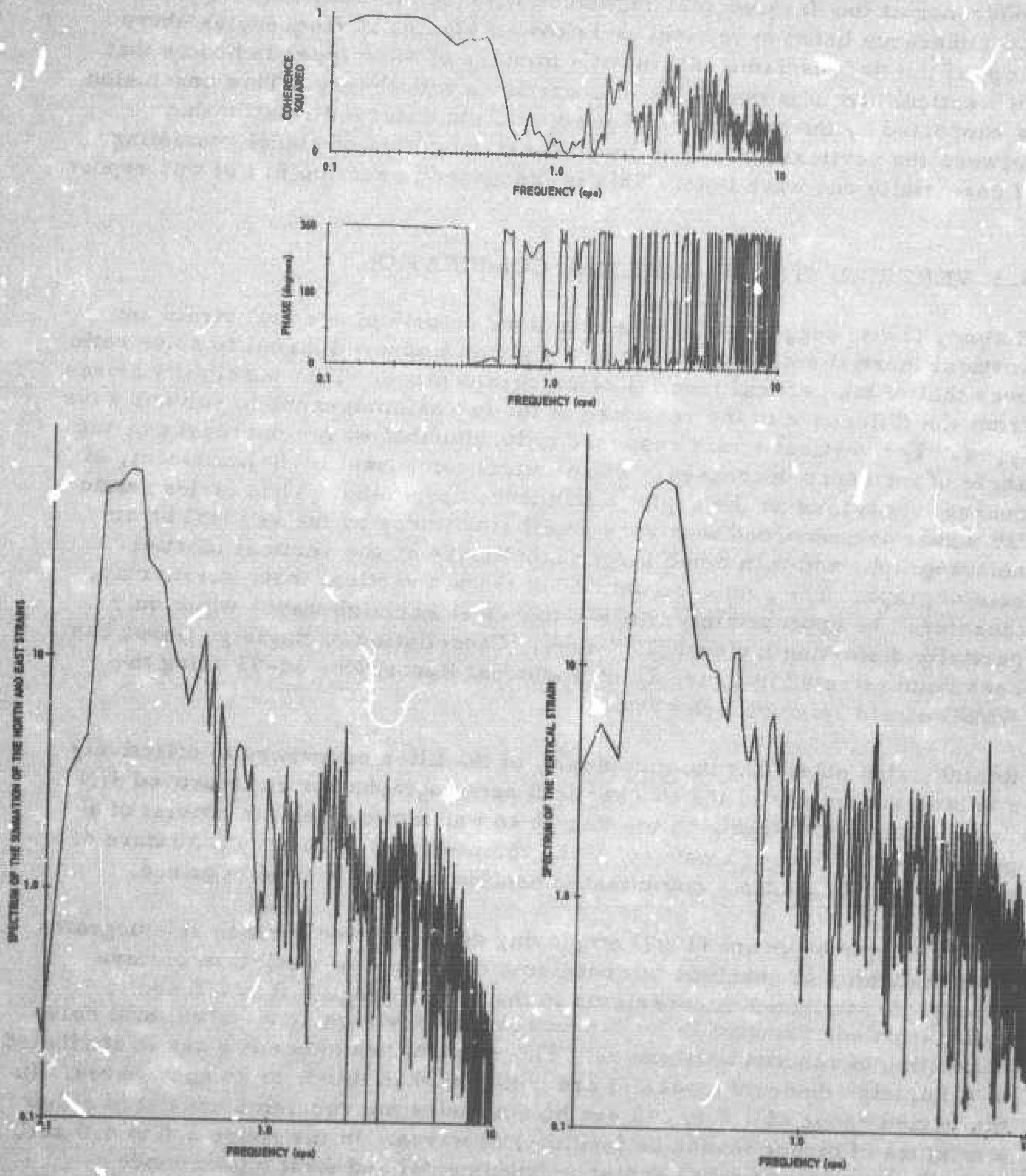

Figure 13. Coherence and phase between and spectra of the vertical strain and summation of the north and east strain (crossed strains) seismograph recordings of microseisms

G 2911

seismographs, vertical or crossed horizontal. The existence of high coherence at low frequencies, combined with the fact that one might expect low coherence between vertical and crossed strains at frequencies above 1 cps if the microseisms consist of a mixture of wave types indicates that the vertical strain is operating in accordance with theory. This conclusion is supported by the agreement of predicted and observed relationships between the vertical strain and inertial seismograms of signal consisting of essentially one wave type. This is discussed in section 5.3 of this report.

5.3 VERTICAL STRAIN - INERTIAL COMBINATION

Romney (1964) suggested that the combined outputs of vertical strain and vertical inertial seismographs might yield an improved signal to noise ratio over that of the vertical inertial seismograph alone. This possibility arises from the difference in the response of the two seismographs to various wave types. The vertical strain response to longitudinal waves decreases as the angle of incidence decreases. The vertical component of displacement, of course, increases as the angle of incidence decreases. Thus, teleseismic 'P' waves are recorded with very small amplitudes by the vertical strain seismograph, and with much larger amplitudes by the vertical inertial seismograph. The combined outputs of the two vertical instruments may, therefore, be appropriately filtered to cancel Rayleigh waves while only partially distorting incident 'P' waves. Cancellation of Rayleigh waves has been demonstrated in figure 10 of Technical Report No. 66-93 using the WMSO strain seismograph system.

Romney also noted that the complexity of the filter necessary to effectively combine the outputs of the two vertical seismographs for an improved S/N ratio will depend largely on the degree to which microseisms consist of a given mode of Rayleigh waves. If the microseisms consist of a mixture of wave types and modes a complicated nonlinear filter will be required.

Investigations by Douze (1967) employing deep well and surface seismograms have lead him to conclude microseisms do consist of a mixture of wave types. He attributes microseisms in the period range 0.3 to 0.8 sec to cultural noise, principally fundamental mode Rayleigh, and noncultural noise consisting of random body waves. The spectral peak near 0.5 sec is attributed to a Rayleigh mode or modes of order higher than third, or to body waves. In the period range of 0.8 to 2.0 sec he concludes microseisms consist of either a mixture of higher modes or longitudinal waves. In the range 2.0 to 4.0 sec, he believes microseisms consist of fundamental and first higher mode Rayleigh or possibly body waves. A number of authors have concluded 6.0 sec microseisms consist primarily of fundamental mode Rayleigh waves.

Coherence between the WMSO vertical strain located in the new borehole and inertial seismograph recordings has been computed for samples of microseisms. Although no attempt to identify specific wave types has been made at this time, the coherence implies that the microseisms are composed of a mixture of wave types and modes. That is, the coherence is computed to be low at most frequencies. Plots of coherence, presented as coherence squared, and the phase of the crossed spectra are illustrated in figure 11.

The phase from 0.1 to 1.0 cps is observed to be relatively constant, $\frac{3\pi}{2}$, for all samples. This is the phase relationship expected for Rayleigh waves. Frequencies above 1.0 cps do not show constant phase relationships from sample to sample. The phases 0, $\frac{\pi}{2}$, and $\frac{3\pi}{2}$ seem to be the most prominent indicating 'P' waves, higher mode Rayleigh, and possibly fundamental mode Rayleigh waves. Since the energy carried by these waves seems to vary with time one cannot anticipate whether the combined vertical strain and inertial seismograph outputs will add or cancel these microseisms at any given time.

Although the phase between 0.1 to 1.0 cps is relatively constant the coherence is low, with exceptions existing in two frequency ranges, below 0.16 cps and near 0.5 cps. Furthermore, low coherence cannot be attributed to just spectral lows. Figure 12 shows low coherence where the spectra are high, for example, near 0.3 and 2.0 cps.

To demonstrate that high coherence exists where the noise consists primarily of one given wave type, two samples recorded several minutes apart containing train noise were examined. Train noise is believed to consist almost exclusively of fundamental mode Rayleigh waves. Figure 13 shows the coherence between the vertical strain and inertial seismographs for the two samples. The coherence at the predominent frequencies of the train noise, 1.6 and 2.6 cps, is seen to be very high as was expected. At frequencies where the train noise is not present the coherence is again observed to be low.

Since some differences exist between the vertical and crossed strains, coherence was computed between samples recorded by the crossed strains and vertical inertial seismograph. The coherence along with that computed between the vertical strain and vertical inertial seismographs for the same sample are illustrated in figure 14. They are essentially the same except beyond 3 cps where the coherence between the two verticals is seen to be a little higher. The coherence is again, in general, low over most of the spectrum for both samples. This indicates that the coherence between the outputs of the vertical displacement seismograph and either the crossed strains or vertical strain seismograph can be expected to be low for microseismic recordings at WMSO.

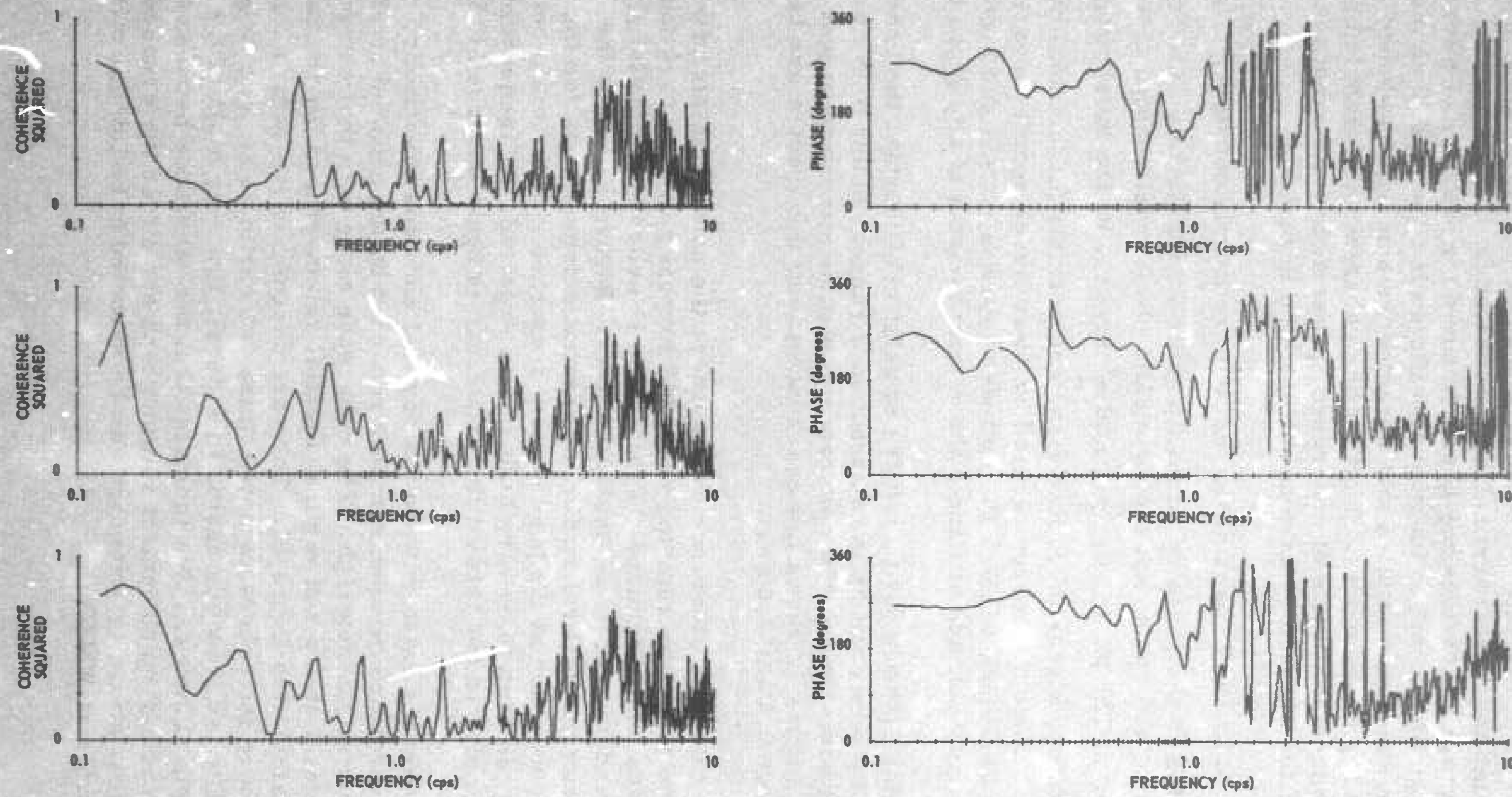

Figure 11. Coherence and phase between the vertical strain and inertial seismograph recordings of microseisms. Three samples are shown.

G 2912

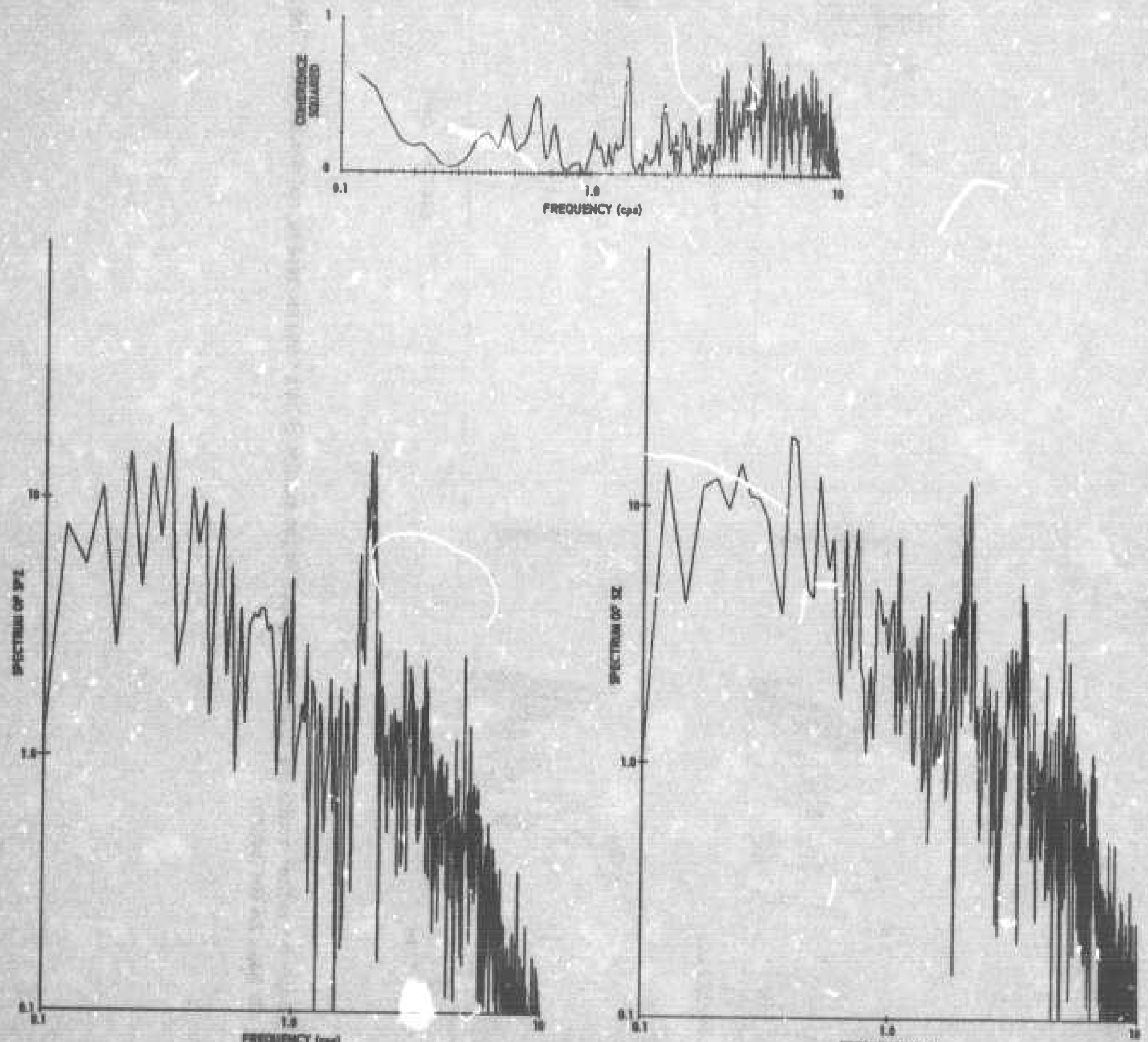

Figure 12. Coherence between and spectra of the vertical inertial (SPZ) and vertical strain (SZ) seismograph recordings of microseisms

G 2913

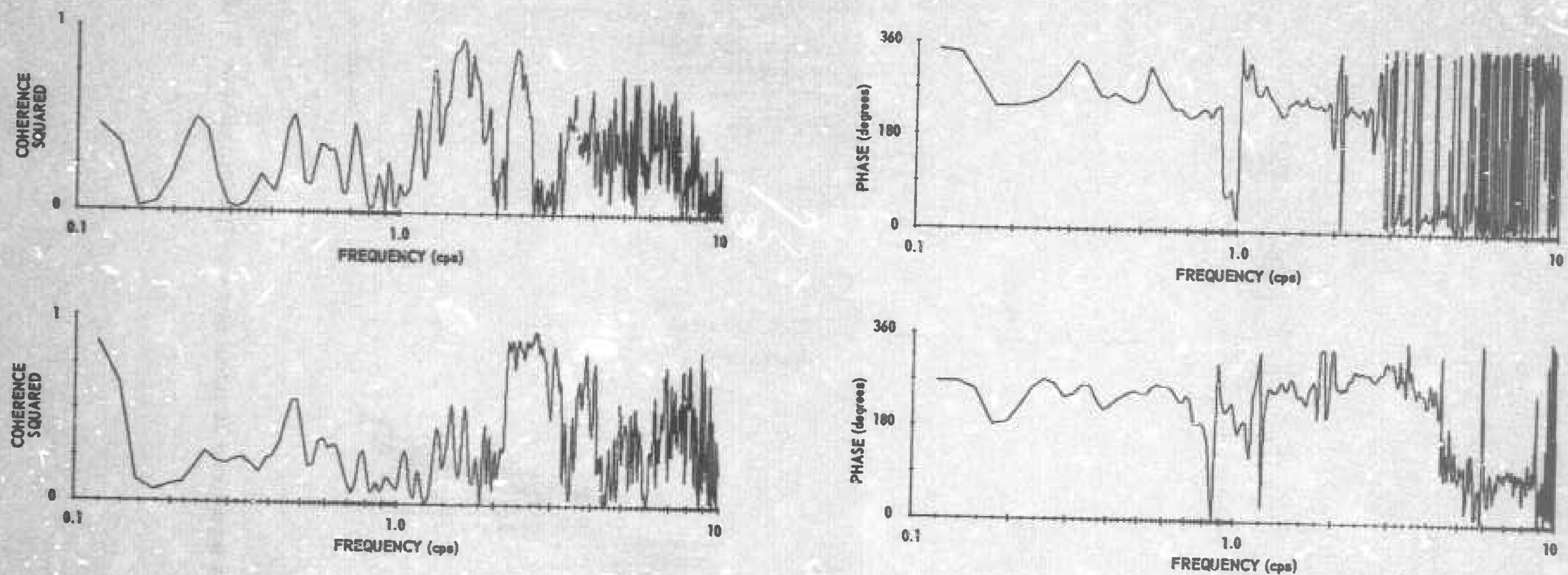

Figure 13. Coherence and phase between the vertical inertial and strain seismographs for two samples of train noise recorded several minutes apart. The predominant frequency of the train noise is 1.6 cps (top), 2.6 cps (bottom)

G 2914

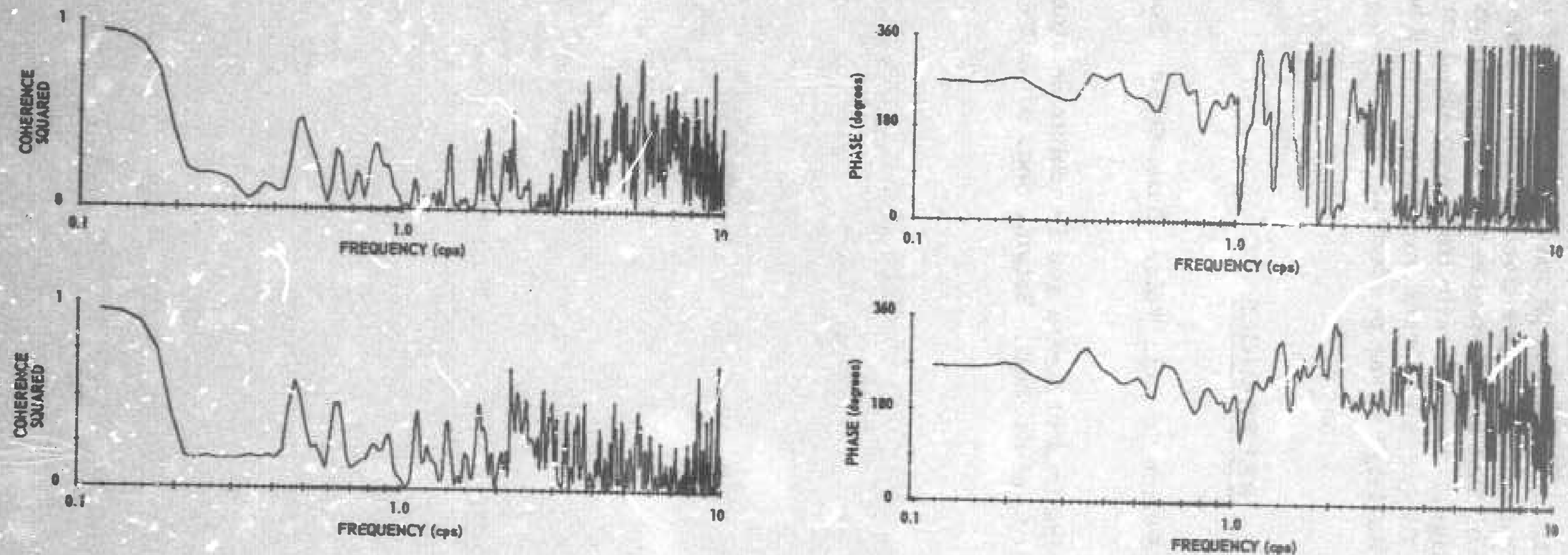

Figure 14. Coherence and phase between the vertical inertial and vertical strain (top), vertical inertial and crossed strain (bottom) seismograph recordings of the same noise sample

G 2915

In conclusion, the vertical strain seismograph may be used to provide significiant information regarding the composition of microseisms. However, a combination of its output with that of a displacement seismograph cannot be used at WMSO to provide a signal-to-noise ratio improvement short of employing a complex nonlinear filter. Significant improvement may be possible at sites where single-mode Rayleigh waves predominate.

6. REFERENCES

Douze, E. J., 1967, Short-Period Seismic Noise; Bull. Seism. Soc. Am., 57, p. 55-81

Romney, Carl, 1964, Combinations of Strain and Pendulum Seismographs for Increasing the Detectability of P: Bull. Seism. Soc. Am., 54, No. 6, Part B, p 2165-2174.

APPENDIX TO TECHNICAL REPORT NO. 67-40

STATEMENT OF WORK TO BE DONE
AFTAC PROJECT AUTHORIZATION NO. VELA T/5081

APPENDIX TO TECHNICAL REPORT NO. 67-40

STATEMENT OF WORK TO BE DONE
AFTAC PROJECT AUTHORIZATION NO. VELA T/5081

EXHIBIT "A"

STATEMENT OF WORK TO BE DONE

AFTAC Project Authorization No. VELA T/5081

1. Instrumentation Development

a. Complete the development of the variable-capacitance transducer to extend the strain seismograph response to longer periods.

b. Complete the modification and testing of the seismometer transducers, amplifiers, filters, and associated circuitry to insure a consistent phase relationship between pendulum and strain seismographs.

c. Design and install secular strain monitors to improve the horizontal strain seismograph operation.

d. Improve the stability of the seismograph circuitry by installing a separate phototube amplifier shelter.

e. Install a variable-capacitance transducer on vertical strain seismometer No. 2 and on the NE horizontal strain seismometer in order to measure the amplitude and phase of the motion actually imparted to the fixed ends of the strain rods during electrical calibration.

2. Seismograph Development

a. Vertical Strain Seismograph

(1) Complete this design of the vertical strain seismograph by improving the anchor design, reshaping the instrument sections, and improving the mechanical reliability relative to installation, position locking, and removal.

(2) Improve the operation of the vertical strain seismograph by incorporating the developments listed in paragraphs 1a, 1b, and 2a(1).

b. Horizontal Strain Seismographs

(1) Improve the design of the horizontal strain seismographs by the addition of secular strain controls and seismograph housing modifications.

(2) Improve the operation of the horizontal strain seismographs by incorporating the developments listed in paragraphs 1a, 1b, 1c, 1d, and 2b(1).

3. Evaluation

a. Vertical Strain Seismograph. Test and evaluate the operation of the improved vertical strain seismograph in a new uncased borehole to be located adjacent to the present cased borehole. The uncased borehole is to be oil-filled and may contain the following features:

(1) Steel casing sections may be used for instrument anchor locations if the sections are decoupled from each other so that longitudinal casing rigidity is less than that of the surrounding rock formation.

(2) A continuous plastic casing may be used to maintain wall smoothness and hole integrity provided that the plastic is more compliant than the surrounding rock formation.

(3) Combinations of (1) and (2) may be used. In all instances where instrument anchors must lock against a borehole liner, the liner must be rigidly bonded to the borehole wall.

To facilitate the positioning of the instrument in the borehole, a permanent anchor may be used in the cased and uncased holes. This fixed depth operation might help to avoid the anchor malfunctioning which has been experienced.

b. Horizontal Strain Seismographs. Test and evaluate the operation of the improved horizontal strain seismographs in their improved housing.

c. Study the effect of the depth of the vertical strain seismometer on the coherence between outputs of the vertical strain seismograph and a pair of horizontal strain seismographs.

4. Applications

a. Record seismic data at Wichita Mountains Seismological Observatory on magnetic tape and 16 mm film; process magnetic tape data at the Geotechnical Corporation's central data processing facility and elsewhere as required; and determine spectra, phase, and coherency among the vertical strain, horizontal strain, and several pendulum seismometer control signals.

b. Experimentally corroborate the vertical strain seismograph performance relative to the 2 crossed-horizontal strain seismographs to verify that true earth strains are faithfully recorded by the vertical strain instrument.

c. Develop a thorough understanding and evaluation of the phase and amplitude performance of the strain seismographs and related pendulum systems.

d. Determine the usefulness of strain seismographs when used singularly and in combination with inertial instruments for wave identification, signal enhancement, detection of long-period signals, and rejection of noise arriving from selected azimuths. Determine the usefulness of strain seismographs in distinguishing between earthquakes and explosions. Schedule the program so as to provide preliminary results on the P-wave enhancement portion of the program not later than 30 Sept 65.

e. Investigate the extent of actual noise suppression and signal enhancement possible through various combinations of the strain and pendulum seismographs at WMSO and compare the results with signal-to-noise improvements predicted by theory.

(1) Collect data from the strain-seismograph system at WMSO and the companion pendulum seismographs.

(2) Analyze the collected data to determine the similarities and differences in character and composition of signals and noise measured by the strain and pendulum instruments.

(3) Ascertain theoretically and demonstrate experimentally the improvement in P-wave detection, enhancement, and identification possible using strain and pendulum seismographs in various combinations.

(4) Analyze a limited number of strain data from at least one other location for comparison with WMSO data.

f. Establish and provide the operation and analysis procedures necessary to operate comparable multicomponent strain seismograph facilities at other locations.

*5. Drawings

Provide drawings and specifications on items specified in paragraphs 2a(1), 2a(2), 2b(1), 2b(2), and the uncased borehole as outlined in paragraph 3 according to Data Items E-23-11.0, E-2-11.0, E-4-11.0, E-5-11.0, E-7-11.0, and T-13-28.0 contained in AFSCM 310-1. These drawings shall conform to the instructions contained in Attachment 2. Wherever Data Items conflict with Attachment 2, the latter will take precedence. Reproduction shall be accomplished in accordance with Data Item E-4-11.0, paragraphs 1b, 1f, 7, 9, 10, 11, and 12c(3), microfilm on aperture cards and non-reproducible paper copies. Index card keypunch format may vary from specifications as approved by AFTAC through the project officer. Aperture cards should be furnished in 2 copies, 1 positive and 1 negative.

6. Reports

Provide monthly, quarterly, final, milestone, and special progress reports in accordance with Data Item S-17-12.0, first sentence of paragraph 1. Wherever the Data Item conflicts with Attachment 1, the latter will take precedence. All reports under this project will be forwarded to HQ USAF (AFTAC/VELA Seismological Center), Wash., D. C. 20333.

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*For the purposes of this contract, the provisions of paragraph 5 of this Exhibit "A" are hereby waived. In lieu thereof, the following provisions shall apply:

"5. Drawings. Drawings shall be furnished in accordance with the provisions of line item 7 of the DD Form 1423 and attachments thereto."

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Geotech A Teledyne Company 3401 Shiloh Road, Garland, Texas 75040	2a. REPORT SECURITY CLASSIFICATION 2b. GROUP

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Multicomponent Strain Seismograph

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5. AUTHOR(S) (Last name, first name, initial)

Girard, B. W., Kirkland, R. H., Sherwin, J. R., and Shopland, R. C.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
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8a. CONTRACT OR GRANT NO. AF 33(657)-15288 b. PROJECT NO. VELA T/5081 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report No. 67-40 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

Qualified requesters may obtain copies of this report from DDC

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	HQ USAF (AFTAC/VELA Seismological Center) Washington, D. C. 20333

13. ABSTRACT

Use of an electromagnetic calibrator in place of the magnetostrictive calibrator on the vertical strain seismometer has eliminated phase discrepancies. Results show that all strain and inertial systems are matched within 4 degrees between 0.1 and 3 cps and within 10 degrees out to 10 cps. An analysis of coherency, phase, and spectra of seismic noise and signals computed by a fast transform BLACKY program shows that the instruments are operating according to theory. Comments relating to the character of the seismic noise are also given. The effects of temperature changes and wind on operation of the horizontal strain seismometers are discussed. Operation of a matched long-period horizontal strain-inertial combination for directional discrimination of long-period surface waves is also discussed.

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